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Metallurgical Calculations: The Electrometallurgy of Iron and Steel

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Metallurgical Calculations.

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The Electrometallurgy of Iron and Steel.

Electrical methods may enter into the extraction of a metal from its ores either as electrolytic or as electrothermal processes. Electrolytic processes are those in which the electric current is used for its electrolytic action, *i. e.*, for its electrical decomposing and depositing properties; electrothermal processes are such as use the current merely as a source of heat, to furnish the sensible heat and high temperature necessary for melting materials or for bringing about chemical reactions. So far electrolytic processes have entered the metallurgy of iron only as used by Burgess for electrolytically refining nearly pure iron in an aqueous electrolyte and depositing chemically pure iron; the electrolysis of fused iron salts has not been practically utilized. Up to the present, electrothermal processes are in commercial use for melting together wrought iron and cast iron to make steel, also for keeping cast iron melted while its impurities are being extracted by oxidation; the electrothermal reduction of iron ores to cast iron has been proved technically possible, and may in some places prove commercially practicable.

ELECTROTHERMAL REDUCTION OF IRON ORES.

If the electric current is used to furnish the heat energy necessary to reduce iron ore, it cannot displace the reducing agent-carbon. In ordinary blast furnace practice the carbon is first burned to provide the heat necessary to smelt down the pig iron and slag, and the product of this incomplete combustion—CO—abstracts oxygen from the ore. The two equations are practically:

At the tuyeres—

$$30C + 15O^2 + 57.15\ N^2 = 30CO + 57.15\ N^2$$

Reduction:

$$4Fe^2O^3 + 30CO + 57.15\ N^2 = 12CO^2 + 18CO + 57.15\ N^2 + 8Fe$$

These equations show us that to produce 8Fe = 448 parts, 30C = 360 parts of carbon is the minimum necessary, which is first burned to CO at the tuyeres, and then the producer gas thus formed (N^2 and CO) reduces the iron oxides above. If the heat for fusion is furnished electrically, the first combustion is unnecessary, all blowing in of air is dispensed with and the reaction taking place is:

$$14Fe^2O^3 + 30C = 12CO^2 + 18CO + 28Fe$$

And we have 28 Fe = 1,568 parts reduced by 30C = 360 parts, a consumption of less than one-third as much carbon as is required in the blast furnace. The operation consists, therefore, in mixing iron ore and carbon so that for every part of iron present about 0.25 parts of carbon is present, using the proper quantity of limestone or other material to flux the gangue of the ore to a fusible slag, and then furnishing electrically the heat necessary to cause the chemical reaction, melt down the resulting iron and slag, and supply radiation losses. The gases resulting from this electrical reduction are combustible, just as the gases from the blast furnace, and since there is no blast to be heated they can very well be utilized to preheat the charges coming into the furnace, and thus save some of the electrical energy needed.

Problem 73.

A magnetite ore contains:

	Per Cent.		*Per Cent.*
Fe^2O^3	60.74	MgO	5.50
FeO	17.18	P^2O^5	0.04
SiO^2	6.60	S	0.57
Al^2O^3	1.48	CO^2	2.05
CaO	2.84	H^2O	3.00

It is to be mixed with pure carbon (charcoal fines) and a suitable flux; the fixed carbon being 0.25 per cent of the iron present; the flux silica sand, so as to make a slag with 33 per cent of SiO^2. Neglect the ash and assume 10 per cent of moisture in the charcoal. Assume also:

(a) The pig iron to contain 4 per cent C, 3.5 per cent Si, 92.4 per cent Fe.

(b) The slag and pig iron to contain at tapping 600 and 400 Calories of heat respectively.

(c) The heat losses by radiation, etc., to be 30 per cent of the total heat requirement of the furnace.

(d) The hot gases to escape at 300° C.

(e) The iron to be completely reduced into the pig iron.

(f) The sulphur to go entirely into the slag as CaS.

Requirements:

(1) The weights of ore, flux and charcoal dust needed per 1,000 kg. of pig iron produced.

(2) A balance sheet of materials entering and leaving the furnace.

(3) A heat balance sheet of the furnace.

(4) The number of kilowatt days of electrical energy required per metric ton of pig iron produced.

Solution:

(1) The ore must supply 924 kg. of iron. But 100 parts of ore contains iron as follows:

		Kg.
In Fe^2O^3	$60.74 \times 112/160$	= 42.52
In FeO	$17.18 \times 56/72$	= 13.36
	Sum	= 55.88

Ore required per 1,000 kg. of pig iron:

$$924 \div 0.5588 = 1{,}654 \text{ kg.} \qquad (1)$$

The slag-forming ingredients from this amount of ore are as follows:

		Kg.
Al^2O^3	$1{,}654 \times 0.0148$	= 24.6
MgO	$1{,}654 \times 0.0550$	= 91.0
CaO	$1{,}654 \times (0.0284 - 0.0057 \times 50/32) = 1{,}654 \times 0.0184$	= 30.4
SiO^2	$(1{,}654 \times 0.0660) - (35 \times 60/28) = 109.2 - 75$	= 34.2
CaS	$1{,}654 \times (0.0057 \times 72/32)$	= 21.2
	Sum	= 201.4

If x parts of SiO^2 sand are added to these, the total weight of slag will be $201.4 + x$, of SiO^2 in it $34.2 + x$. And since the SiO^2 is to be 33 per cent of the weight of slag, then

$$34.2 + x = 0.33\ (201.4 + x)$$

whence $x = 48$ kg. (1)

The charcoal dust used must contain fixed carbon equal to 0.25 of the iron present, *i. e.*,

$$924 \times 0.25 = 231 \text{ kg.}$$

And since it is 90 per cent fixed carbon the dust required is:

$$231 \div 0.90 = 257 \text{ kg.} \qquad (1)$$

Charges.		*Pig Iron.*		*Slag.*		*Gases.*	
Ore....1654 Kg.							
Fe^2O^3....	1004.6	Fe.....	703.2	.....		O.....	301.4
FeO.....	284.2	Fe.....	221.0	.....		O.....	63.2
SiO^2.....	109.2	Si.....	35.0	SiO_2...	34.2	O.....	40.0
Al^2O^3....	24.6	.....		Al_2O_3..	24.6	.....	
CaO.....	46.9	.....		CaO...	30.4	O.....	4.7
MgO.....	91.0	.....		MgO...	91.0	.....	
P^2O^5.....	0.6	P.....	0.3	Ca.....	11.8	O.....	0.3
S.....	9.4	.....		S.....	9.4	.....	
CO_2.....	33.9	.....		.....		CO_2....	33.9
H^2O.....	49.6	.....		.....		H_2O...	49.6
Flux... 48 Kg.							
SiO^2.....	48.0	.....		SiO_2...	48.0	.....	
Charcoal257Kg.							
C.....	231.0	C.....	40.0	.....		C.....	191.0
H^1O.....	26.0	.....		.....		H_2O...	26.0
	1959.0		999.5		249.4		710.1

(3) Heat available is the heat of oxidation of carbon plus that furnished by the electric current. The charge gives up to the carbon, as shown on the balance sheet, 301.4 + 63.2 + 40.0 + 4.7 + 0.3 = 409.6 kg. of oxygen. The 191 kg. of carbon burned would take 191 × 16/12 = 254.7 kg. of oxygen to burn it to CO, leaving 154.9 kg. of oxygen to burn CO to CO^2. This would burn 154.9 × 28/16 = 271.1 kg. of CO to CO^2.

The heat of formation of the slag may be taken as approximately 150 Calories per kg. of contained $SiO^2 + Al^2O^3$. The heat of combination of carbon with the iron is a doubtful quantity, which may be taken at 705 Calories per kilogram of carbon. The formation of CaS gives 2,947 Calories per kilogram of sulphur.

Letting the heat furnished by the electric current = x, and neglecting the heat of oxidation of the small amount of electrode carbon consumed, we have:

Heat Available.

		Calories.
Supplied by electric current:		x
Oxidation of C to CO	191 × 2,430 =	464,130
Oxidation of CO to CO^2	271.1 × 2,430 =	658,770
Formation of silicate slag	106.8 × 150 =	16,020
Formation of CaS	9.4 × 2,947 =	27,700
Formation of Fe^3C	40. × 705 =	28,200
	Sum =	1,194,820 + x

Heat Distribution.

	Calories.
Reduction of Fe from Fe^2O^3 163.2 × 1,746	= 1,229,790
Reduction of Fe from FeO 221.0 × 1,173	= 259,230
Reduction of Si from SiO^2 35.0 × 7,000	= 245,000
Reduction of P from P^2O^5 0.3 × 5,892	= 1,770
Reduction of Ca from CaO 11.8 × 3,288	= 38,800
Expulsion of CO^2 from ore 33.9 × 1,026	= 34,780
Evaporation of H^2O from charges 75.6 × 606.5	= 45,850
Sensible heat in gases, at 300°	
CO 174.6 kg. = 138 m^3 × 0.311 = 42.9	
CO^2 459.9 kg. = 232 m^3 × 0.436 = 101.1	
H^2O 75.6 kg. = 93 m^3 × 0.385 = 35.8	
179.8 × 300 =	53,940
Sensible heat in slag 249.4 × 600 =	149,640
Sensible heat in pig iron 1,000 × 400 =	400,000
Loss by radiation, etc., 0.30 (1,194,820 + x) =	358,450 + 0.3 x
Sum total =	2,817,250 + 0.3 x

Equating the heat available and accounted for we have:

$$1{,}194{,}820 + x = 2{,}817{,}250 + 0.3\,x.$$

Whence x = 2,317,760 Calories.

And the sum total of heat requirement is

3,512,580 Calories,

of which the electric current supplies

$$\frac{2{,}317{,}760}{3{,}512{,}580} = 0.66 = 66 \text{ per cent.} \qquad (3)$$

(4) A kilowatt-day of electricity is equal to

0.239 × 60 × 60 × 24 = 20,650 Calories.

There is, therefore, required per ton of pig iron produced:

$$\frac{2{,}317{,}760}{20{,}650} = 112 \text{ kilowatt days.} \qquad (4)$$

This figure might be materially reduced by using the waste gases to warm up the charges entering the furnace. It is also possible that in a properly designed shaft the gases passing out might contain nearly equal volumes of CO and CO^2, instead of 3CO to 2CO, as assumed in this problem, from best ordinary blast furnace practice. Any greater utilization of the heat-producing power of the carbon would decrease the electrical energy required; the above calculated value is given as a safe figure for this ore on which to base working calculations.

Problem 74.

At Sault Sainte Marie, Canada, roasted pyrrhotite ore was smelted with the addition of limestone and charcoal fines. The mixture used contained 400 pounds of ore, 110 pounds charcoal dust and 85 pounds limestone. The analyses of each of these materials was:

Roasted Ore.		*Limestone.*		*Charcoal Dust.*	
Fe^2O^3	65.43	CaO	52.00	Fixed C	55.90
CuO	0.51	MgO	2.10	Vol. matter	28.08
NiO	2.84	Fe^2O^3	0.60	Moisture	13.48
SiO^2	10.96	Al^2O^3	0.21	Ash	2.54
Al^2O^3	3.31	SiO^2	1.71		
CaO	3.92	P^2O^5	0.01		
MgO	3.53	SO^3	0.13		
SO^3	3.90	CO^2	43.15		
P^2O^5	0.03				
H^2O	5.57				

Using 165.65 kilowatts effective electric energy for 56 hours 20 minutes, there was produced 7,336 pounds of nickeliferous pig iron and 5,062 pounds of slag, having the following average compositions:

Pig Iron.		*Slag.*	
C	3.05	SiO^2	16.44
Si	5.24	Al^2O^3	13.86
S	0.01	CaO	42.87
P	0.05	MgO	8.80
Cu	0.81	CaS	13.34
Ni	3.94	FeO	0.84
Fe	86.90	Undetermined	3.85

Requirements:

(1) A balance sheet of materials entering and leaving the furnace.

(2) A heat balance sheet of the furnace, making necessary assumptions where data is not furnished.

(3) The thermal efficiency of the furnace.

Solution:

(1) The amount of ore used may be calculated either from the iron, the nickel or the copper. The nickel and copper are the easiest to use, because there is supposed to be none of them in the slag, but they are the least reliable, because present in such small amount. The pig-metal contains 7,336 × 0.81 = 59.4 pounds of copper, and since the roasted ore contains 0.51 × 63.6/79.6 = 0.41 per cent copper, the weight of ore used, on this basis, would be 59.4 ÷ 0.0041 = 14,493 pounds. As for nickel, the pig-metal contains 7,336 × 0.0394 = 289 pounds of nickel, and since the roasted ore contained 2.84 × 59/75 = 2.23 per cent, the weight of this used should have been 289 ÷ 0.0223 = 12,960 pounds. These figures differ so much that we will make the calculation on the basis of the iron. There is iron present as follows:

	Pounds.
In the pig iron 7,336 × 0.8690	= 6,375
In the slag 5.062 × 0.0084 × 56/72	= 33
Total in products	= 6,408

In 100 pounds of ore 65.43 × 0.7	= 45.80
In 21 pounds limestone 21. × 0.0060 × 0.7	= .08
In 27.5 pounds of charcoal 27.50 × 0.0025 × 0.7	= .04
In charge, per 100 pounds of ore used	= 45.92

Therefore, ore necessary to supply the iron in products:

	Pounds.
6,408 ÷ 0.459	= 13,961

with which will be used:

Charcoal = 13,961 × 110/400	= 3,839
Limestone = 13,961 × 85/400	= 2,967

We are now ready to construct the balance sheet as soon as we assume probable values for the composition of the volatile matter and ash of the charcoal. The ash might be taken as containing on an average: K^2O 15 per cent, CaO 40, MgO 20, MnO 15, and Fe^2O^3 10 per cent. The volatile matter is due to insufficient charring, and the gases given off on heating may be assumed as, by volume, CO^2 25 per cent, CO 15, H^2 50, CH^4 10. This would make the volatile matter to contain, in per cents by weight, carbon 33.7, oxygen 58.5, hydrogen 7.8 per cent. (The verification of this last statement is a nice little exercise in chemical arithmetic.) The full statement of the elementary composition of the charcoal, for use in making the balance sheet, is therefore:

	Per Cent.	
Fixed carbon	55.90	
Volatile carbon	9.46	28.08%
Volatile hydrogen	2.19	
Volatile oxygen	16.43	
Moisture	13.48	
K^2O	0.38	2.54%
CaO	1.02	
MgO	0.51	
MnO	0.38	
Fe^2O^3	0.25	

Balance Sheet, per 7,336 Lbs. Pig-metal.

Charges.		*Pig-metal.*		*Slag.*		*Gases.*	
Roasted Ore	13,961						
Fe^2O^3	9,135	Fe	6,375	FeO	25	O	2,735
NiO	397	Ni	289	NiO	28	O	80
CuO	71	Cu	59			O	12
SiO^2	1,530	Si	384	SiO^2	1,091	O	55
Al^2O^3	461			Al^2O^3	461		
CaO	547			CaO	166	O	109
MgO	493			MgO	493		
SO^3	545	S	1	CaS	490	O	327
P^2O^5	4	P	4			O	0
H^2O	778					H^2O	778
Limestone	2,967						
CaO	1,543			CaO	1,542	O	0
MgO	62			MgO	62		
Fe^2O^3	18			FeO	16	O	2
Al^2O^3	6			Al^2O^3	6		
SiO^2	51			SiO^2	51		
P^2O^5	0			P^2O^5	0		
SO^3	4			CaS	4		
CO^2	1,280					CO_2	1,280
Charcoal dust	3,839						
Fixed C	2,146	C	224			C	1,922
Vol. C	363					C	363
Vol. H	84					H	84
Vol. O	631					O	631
H^2O	518					H_2O	518
K^2O	15			K^2O	15		
CaO	39			CaO	39		
MgO	20			MgO	20		
MnO	15			MnO	15		
Fe^2O^3	10			FeO	9	O	1
Electrode	66						
C	66					C	66
	20,828		7,336		4,533		8,962

There is a lack of close correspondence between the weights and compositions of slag, as observed and as calculated, due evidently to inaccurate sampling and analyses of the roasted ore and slag.

(2) From the balance sheet we can deduce the heat evolved and absorbed in the chemical reactions in the furnace. The more involved items are calculated as follows:

Oxidation of carbon to CO: All the carbon put into the furnace as fixed carbon goes out as either CO or CO^2, except that going into the pig iron. The carbon burnt to CO in the furnace may be, therefore, taken as 1,922 + 66 = 1,988 pounds, evolving 1,988 × 2,430 = 4,830,800 pound-Calories.

Oxidation of CO to CO^2: There is given up in the furnace, by the reductions accomplished, 3,021 pounds of oxygen, of which 1,988 × 16/12 = 2,651 pounds would burn fixed carbon to CO, as above shown, leaving 370 pounds to burn CO to CO^2. This would oxidize 370 × 28/16 = 648 pounds of CO to CO^2, which would evolve 648 × 2,430 = 1,574,600 pound-Calories.

Heat energy of electric current: One kilowatt-second is 0.239 kilogram-Calories, or 0.527 pound-Calories. The current being on 56 hours 20 minutes, or 202,800 seconds, the heat equivalent of the current used is:

0.527 × 202,800 × 165.65 = 17,704,000 pound-Calories.

Heat in escaping gases: We are here confronted with the fact that no observation of the temperature of these was given. There is no essential reason why they should escape very hot from the furnace, if properly run and conducted, so we will assume a maximum temperature of 500° C. The gases would consist of 1,958 + 2,651 — 648 = 4,061 pounds of CO and 648 + 370 = 1,018 pounds of CO^2, from the oxidation of fixed carbon in the furnace; plus 1,280 of CO^2 from the limestone, and 666 pounds CO^2, 254 pounds CO, 97 pounds CH^4 and 60 pounds of H^2 from the volatile matter of the charcoal. To these must be added 1,290 pounds of water vapor. The heat is, therefore:

CO	4,315 lbs. = 54,800 ft³ × 0.304 =	16,650	oz. Cal.
CO^2	2,964 lbs. = 23,950 ft³ × 0.480 =	11,500	"
CH^4	97 lbs. = 2,150 ft³ × 0.490 =	1,050	"
H^2	60 lbs. = 10,700 ft³ × 0.304 =	3,250	"
H^2O	1,290 lbs. = 25,500 ft³ × 0.415 =	10,550	"
	Sum = 117,100 ft³	43,000	" per 1°
		= 21,500,000	" per 500°
		= 1,343,750	lb.-Cal.

The other items of the heat balance sheet are almost self-explanatory, and the complete balance is as follows:

Heat Available.

	Pounds-Cal.
Energy of the electric current	= 17,704,000
Oxidation of C to CO	= 4,830,800
Oxidation of CO to CO^2	= 1,574,600
Combination of C with Fe^3 224 × 705	= 157,900
Combination of Ca with S 220 × 2,947	= 648,300
Formation of silico-aluminate slag (SiO^2 + Al^2O^3) 1,609 × 150	= 241,400
Total	= 25,157,000

Heat Distribution.

Reductions:

Fe^2O^3 to Fe	6,375 × 1,746 =	11,130,750
NiO to Ni	289 × 1,051 =	303,750
CuO to Cu	59 × 593 =	35,000
SiO^2 to Si	384 × 7,000 =	2,688,000
SO^3 to S	218 × 2,872 =	626,100
P^2O^5 to P	4 × 5,892 =	23,550
CaO to Ca	274 × 3,288 =	900,900
Fe^2O^3 to FeO	50 × 446 =	22,300
Expulsion of CO^2 from flux:		
	1,280 × 1,026 =	1,313,300

Evaporation of H^2O	1,290 × 606.5	=	783,400
Sensible heat in gases		=	1,343,750
Sensible heat in pig iron	7,336 × 400	=	2,934,400
Heat in slag	4,533 × 600	=	2,719,800
Loss by radiation, conduction, etc		=	332,000
		Total =	25,157,000 (2)

(3) The essential work done by the furnace is the reductions, evaporation of moisture and decomposition of carbonates. The heat in slag, iron, gases and radiation loss are all susceptible of diminution or of being more or less returnable to the furnace. The usefully applied heat is, therefore, 17,827,050 pound-Calories. To produce this there was consumed the 25,157,000 pound-Calories actually generated, and there was wasted 13,390,000 pound-Calories, the calorific power of the gases escaping from the furnace, which should have been generated or might be utilized, making a total of 38,527,000 pound-Calories disposable.

The working thermal efficiency over all was therefore:

$$\frac{17,827,050}{38,527,000} = 0.46 = 46 \text{ per cent.} \qquad (3)$$

Production of Steel.

There are three methods of producing steel electrically which are practicable. First, the electric furnace may replace the crucible simply as a melting apparatus, in producing a cast steel from cemented bars; second, the electric furnace may replace the crucible or open-hearth furnace as an apparatus in which to melt together wrought iron and pure cast iron, such as washed pig metal, although in this operation the electric furnace is more like the crucible method, in that there is not necessarily any oxidation of the metal or of its impurities in the operation; third, the electric furnace may be used to melt or keep melted cast iron, while its impurities are oxidized out by additions of iron ore, in this operation resembling the Uchatius method of making crucible steel or the "pig and ore" process of making steel in the open-hearth furnace.

The particular advantages possessed by the electric furnace processes are, compared with the crucible process, the larger quantities in which the steel can be made in one operation, the absence of carbon in the furnace lining, thus controlling better the carbon and silicon in the steel, and the higher temperature, enabling a more basic slag to be kept fluid and thus sulphur to be better eliminated; the advantages compared with the open-hearth furnace are the absence of gases of combustion in contact with the metal, and the higher temperature available, which permits of very basic, refractory slags being made and kept thinly fluid, and thus gives better control of sulphur and phosphorus. In addition to these, in both cases, may be mentioned the commercial advantages, for the saving in crucibles alone makes the electric furnace superior in this respect to the crucible process, and the electric furnace can compete successfully as regards cost with the regenerative open-hearth furnace wherever water power costs less than $10.00 per horse-power-year and coal costs over $5.00 per ton.

A particular point to be noted is, that when heating by combustion is used the efficiency of the absorption of heat by the charges decreases very rapidly as the temperature gets higher. For instance, if a cold ingot of iron is placed in a furnace the temperature of which is 1,500°, the iron absorbs heat with very great rapidity from the start up to, say, 1,000°, but with decreasing rapidity thereafter. The rate of transfer of heat from the gases to the iron is proportional to the difference of temperature, and is some fifteen times as fast when the iron is at 0° as when it is at 1,400°. If the efficiency of the heating by furnace gases is, say, 25 per cent in bringing metal up to 1,500°, it is likely that the distribution of this efficiency is distributed about as follows:

Heating from 0° to 500°	45	per cent efficiency
Heating from 500° to 1,000°	27	" "
Heating from 1,000° to 1,500°	3	" "

On the other hand, the conversion of electrical energy into heat in the substance of the material to be heated is not a contact or transfer phenomenon, but a thermodynamically frictionless transfer of 100 per cent efficiency, and equally so at the highest as at the lowest temperatures. Only radiation and conduction losses need be considered, the problem is not how much heat can you *get* into a body but how much can you *keep* in; it is already all in, 100 per cent of it, to start with. In a large, properly designed electric furnace the radiation and conduction losses of heat, even working to the highest temperatures, can be kept at 15 to 25 per cent of the total heat generated, giving an efficiency of 75 to 85 per cent.

It may very well be, that there are places where the relative prices of coal and electric power are such that coal is the cheaper for heating to 500°, at 45 per cent efficiency, or to 1,000° at 36 per cent efficiency, or even to 1,500°, at 25 per cent efficiency, but that the combination of heating by fuel to 1,000° at 36 per cent efficiency and then by electricity from 1,000° to 1,500°, at 70 per cent efficiency, would be the cheaper plan, or even by fuel to 500°, at 45 per cent efficiency, and then by electricity from 500° to 1,500°, at, say, 75 per cent efficiency, would be commercially advantageous.

Illustration: Steel bars are to be melted in an electrical furnace. It takes 300 Calories effective in the steel per kilogram to heat it to a tapping heat; the electric furnace supplies this at a net thermal efficiency of 75 per cent. To heat the bars to 750°, cherry red, without melting them, requires 88 Calories, or 29 per cent of the total. If the bars were heated in a coal furnace to 750°, and then transferred to the electric furnace, some 25 per cent of the electrical power might be saved. If this heating were done by coal having a calorific power of 8,500, at a thermal efficiency of 25 per cent, there would be needed 40 grams of coal. The question is, therefore, the relative cost of 88 ÷ 0.75 = 117 Calories delivered electrically and 40 grams of coal. The former requires 117 ÷ 0.239 = 490 kilowatt-seconds = 8.2 kilowatt-minutes = 0.14 kilowatt-hours. At $10.00 per kilowatt-year (8,760 hours) this would cost 0.14 × 0.114 = 0.016 cents. At $5.00 per metric ton the coal would cost 0.040 × 0.5 = 0.020 cent. Under such assumed conditions of cost of power and of coal the electrical heating, even up to 750°, would be the cheaper.

Problem 74

In an induction electric furnace of 170 kilowatts capacity, 4.7 tons of steel is made per day by melting together cold-washed pig iron and scrap iron, the melted steel carrying 350 Calories per kilogram.

Required:

(1) The electric energy in kilowatt hours required per ton of steel produced.

(2) The thermal efficiency of the furnace.

(3) If one-third the material used were put into the furnace melted, carrying 275 Calories per kilogram, what would be the production per day and the power required per ton of steel?

Solution:

(1) Energy for 4.7 tons		=	170 kw-days.
Energy for 1.0 ton		=	36.2 "
Energy for 1.0 ton		=	0.10 kw-year
Energy for 1.0 ton		=	869 kw-hours. (1)
(2) 1 kw-hour = 0.239 × 60 × 60		=	860 Calories.
869 kw-hours		=	747,340 "
Heat in 1 ton of steel = 350 × 1,000		=	350,000 "

$$\text{Thermal efficiency} = \frac{350,000}{747,340} = 0.47 = 47 \text{ per cent.}$$

(3) Heat in melted material used per kilogram of steel produced = 275 × 1/3 = 92 Calories.

Heat to be supplied by the current 350 — 92 = 258 Calories.

Production per day under these conditions:

$$4.7 \times \frac{350}{258} = 6.4 \text{ tons.} \quad (3)$$

Relative times for the heats = 1 to 0.74.

Energy required per ton = 170 ÷ 6.4 = 26.6 kw-days.
= 0.07 kw-year.
= **638** kw-hours. (3)

Problem 75.

An electric steel furnace running at full heat, and containing about 2,500 kg. of steel, loses by radiation, etc., 250,000 Calories per hour; 2,500 kg. of melted pig iron is run into the hot furnace, carrying 250 Calories per kilogram, and it is treated with 500 kg. of iron ore, previously heated to 500° C., and 50 kg. of limestone added cold. The steel produced carries 400 Calories per kilogram and the slag 600 Calories. The operation lasts 1 hour. Assume the following composition of materials used and made:

Pig Iron.	*Iron Ore.*	*Limestone.*	*Steel.*
Fe.....96.656	Fe_2O_3....85.93	CaO.....53.74	Fe.....99.60
C..... 2.700	FeO..... 3.96	MgO..... 0.17	C..... 0.11
Si..... 0.600	SiO_2..... 5.50	SiO_2..... 3.14	Si..... 0.11
Mn.... 0.025	MnO..... 0.63	Fe_2O_3.... 0.18	Mn..... 0.15
S..... 0.007	Al_2O_3.... 0.76	Al_2O_3.... 0.32	S..... 0.02
P..... 0.012	CaO..... 2.23	P_2O_5.... 0.006	P..... 0.01
	MgO..... 0.97	S..... 0.001	

The bath was treated by the final addition of 10 kg. of cold ferro-manganese, carrying 80 manganese, 16 iron and 4 carbon. The steel obtained weighed 2,630 kg.

Required:

(1) A balance sheet of materials entering and leaving the furnace.

(2) The weight and percentage composition of the slag.

(3) A balance sheet of the heat received and distributed.

(4) The net power required to run the furnace and the cost of power per ton of steel made, at $25.00 per kilowatt-year.

Balance Sheet.

Charges.	*Steel.*	*Slag.*	*Gases.*
Pig iron.....(2500 Kg.)			
Fe.....2416.4	2416.4	.....	.....
C..... 67.5	2.5	.....	C..... 65.0
Si..... 15.0	2.9	SiO^2.... 24.9	.....
Mn..... 0.6	.....	MnO.... 0.8	.....
S..... 0.2	0.5	.....	.....
P..... 0.3	0.3	.....	.....
Ore.....(500 Kg.)			
Fe^2O^3..... 429.7	203.1	FeO.....125.6	O..... 87.2
FeO..... 19.8	.....	FeO..... 19.8	.....
SiO^2..... 27.5	.....	SiO^2.... 27.5	.....
MnO..... 3.2	.....	MnO.... 3.2	.....
AlO^{23}..... 3.8	.....	Al^2O^3... 3.8	.....
CaO..... 11.2	.....	CaO.... 11.2	.....
MgO..... 4.8	.....	MgO.... 4.8	.....
Limestone.....(50 Kg.)			
CaO..... 26.9	.....	CaO.... 26.9	.....
MgO..... 0.1	.....	MgO.... 0.1	.....
SiO^2..... 1.6	.....	SiO^2.... 1.6	.....
Fe^2O^3..... 0.1	.....	FeO..... 0.1	.....
Al^2O^3..... 0.2	.....	Al^2O^3... 0.2	.....
CO^2..... 21.2	.....	.....	CO_2.... 21.2
Ferro-manganese (10 Kg.)			
Fe..... 1.6	1.6	.....	.....
C..... 0.4	0.4	.....	.....
Mn..... 8.0	3.9	MnO.... 5.3	.....
3060.0	2631.6	255.8	173.4

(2) The slag contains:

		Per Cent.
SiO^2	54.0 pounds	= 21.1
Al^2O^3	4.0 "	= 1.5
CaO	38.1 "	= 14.9
MgO	4.9 "	= 1.9
FeO	145.5 "	= 56.9
MnO	9.3 "	= 3.6
	255.8 "	= 99.9 (2)

Heat Available.

		Calories.
Electric current:		x
Oxidation of C to CO	65.0 × 2,430 =	157,950
Oxidation of CO to CO^2	0.9 × 2,430 =	2,190
Oxidation of Si to SiO^2	12.1 × 7,000 =	84,700
Oxidation of Mn to MnO	4.7 × 1,653 =	7,770
Formation of slag	22.6 × 150 =	3,390
Heat in melted pig iron	2,500 × 250 =	625,000
Heat in iron ore	500 × 77 =	38,500
	Sum = x +	919,500

Heat Distribution.

		Calories.
Heat in melted steel	2,630 × 400 =	1,052,000
Heat in melted slag	256 × 600 =	153,600
Reduction of Fe^2O^3 to FeO	386.7 × 446 =	172,470
Reduction of FeO to Fe	203.1 × 1,173 =	238,240
Separation of carbon from iron	65 × 705 =	45,800
Heat in gas at 1,500°:		
CO = 151.7 kg. = 120.4 m^3 × 0.32 × 500	=	19,260
CO^2 = 1.4 kg. = 0.7 m^3 × 0.60 × 500	=	200
Loss by radiation, etc.	=	250,000
	Total =	1,931,570

Heat to be supplied by current:

x = 1,931,570 — 919,500 = 1,012,070 Calories. (3)

(4) One kilowatt furnishes per hour 860 Calories, therefore, the power required to run the furnace is:

1,012,070 ÷ 860 = 1,177 kilowatts. (4)

At $25.00 per kilowatt-year a kilowatt-hour would cost

$25.00 ÷ 8,760 = 0.2854 cents.

And the power to run the furnace 1 hour would cost

0.002854 × 1,177 = $3.36.

And the cost per ton of steel:

$3.36 ÷ 2.630 = **$1.32.** (4)

Problem 76.

It is desired to design a plant for the electro-deposition of pure iron by the Burgess process (see Transactions American Electrochemical Society, Vol. V., p. 201). The desiderata and data are as follows:

Output, 25 metric tons per day.

Current density, 110 amps. per square meter.

Anodes, 0.75 × 0.5 meters immersed × 3 m.m. thick.

Cathodes, 0.75 × 0.5 meters immersed × 1 m.m. thick at starting.

Cathodes to be run until deposit is 1.5 c.m. thick on each side.

Anodes run until 0.9 consumed.

Tanks, 1.00 meter deep, 0.6 m. mide, 2 m. long inside, filled to within 0.10 meter of top with electrolyte.

Working distance between anode and cathode 6 centimeters at starting.

Electrolyte contains 10 per cent $FeSO^4$, $7H^2O$, and 5 per cent $(NH^4)^2SO^4$, specific gravity 1.1, electrical resistivity 20 ohms per centimeter cube.

Voltage drop in connections and conducting rods 0.3 volt per tank.

Main conductors carry 2 amps. per m.m. square of section.

Net cost of electrical power, $25.00 per kilowatt-year.

Requirements:

(1) The number of anodes and cathodes per tank and the number of tanks in the plant and their arrangement.

(2) The weight of anodes and cathode sheets, increasing the weight of immersed part 10 per cent. Specific gravity of the rolled iron 7.9.

(3) The weight of ferrous sulphate and ammonium sulphate required to start the plant.

(4) The drop of potential across the electrodes at starting

and at the close of a deposition; the drop of potential per tank; the total voltage needed at starting the plant and when it is in regular operation.

(5) The cross sectional area of the main conductors.

(6) The time required to consume an anode plate, *i. e.*, in dissolving iron away equal to 0.9 of its weight.

(7) The time required to deposit a full cathode plate; specific gravity of the deposit 7.6.

(8) The electric power required to run the plant and its cost per ton of iron deposited.

Solution:

(1) 110 amps. per square meter deposits per day:

$$0.00001036 \times 110 \times \frac{56}{2} \times 60 \times 60 \times 24 = 2{,}757 \text{ grams Fe.}$$

Therefore, depositing surface required:

$$25{,}000 \div 2.757 = 9{,}140 \text{ square meters.}$$

Since one cathode plate has a depositing area on both sides of $0.75 \times 0.5 \times 2 = 0.75$ square meter, the number of cathode plates required in the whole plant is:

$$9{,}140 \div 0.75 = 12{,}187.$$

In one tank, if there are x cathodes and $x + 1$ anodes, the thickness of these plates at starting is, in millimeters, $x + 3(x + 1) = 4x + 3$ m.m. The number of spaces between anodes and cathodes being $2x$, and each of these being 6 c.m. = 60 m.m. at starting, the spaces are $120x$ m.m. The length of the tank being, inside, 2,000 m.m.:

$$124x + 3 = 2{,}000$$

whence $$x = 16.1.$$

Each tank will therefore contain 16 cathodes and 17 anodes, at a distance apart, at starting of

$$\frac{2{,}000 - 16 - 3(17)}{2(16)} = 60.4 \text{ m.m.} = \mathbf{6.04} \text{ c.m.} \quad (1)$$

Since we need 12,187 cathode plates we need

$$12{,}187 \div 16 = 761.7 \text{ tanks.}$$

Which means that we would use **762** tanks. (1)

The arrangement of the tanks in series and groups of series can be best discussed when we know the voltage drop per tank, grouping them so as to absorb either 110 or 220 volts per series in one group.

(2) An anode sheet weighs:

$$75 \times 50 \times 0.3 \times 7.9 \times 1.1 = 9{,}776 \text{ grams,}$$

of which there is immersed 8,888 grams.

The 17 anodes per tank weigh altogether:

$$9.776 \times 17 = 166.2 \text{ kg.,}$$

and the 16 cathodes, which are one-third as thick:

$$3.259 \times 16 = 52.1 \text{ kg.}$$

In the whole plant, at starting, the weights will be:

Anode sheets	$166.2 \times 762 =$	**126,644** kg.	
Cathode sheets	$52.1 \times 762 =$	**39,700** "	(2)

(3) Volume of liquid in tank:

$(1 - 0.1) \times 0.6 \times 2$	=	1.08 cubic meters.
Weight of solution per tank:		
$1.08 \times 1{,}000 \times 1.1$	=	1,188 kg.
Weight of dissolved salts:		
Copperas	=	118.8 "
Ammonium sulphate	=	59.4 "
Weight in the whole plant:		
Copperas	=	90.5 tons.
Ammonium sulphate	=	**45.3** " (3)

(4) At starting the surface of the electrodes are 6.04 c.m. apart, and 110 amps. passes through each square meter of electrode surface; therefore, $110 \times 0.375 = 41.25$ amps. pass from each free side of each anode plate to the corresponding side of a cathode plate. Neglecting the small cross sectional area of electrolyte outside the plates, the resistance of each space would be

$$\frac{20 \times 6.04}{75 \times 50} = 0.0322 \text{ ohms,}$$

and the drop of voltage across two electrodes:

$$0.0322 \times 41.25 = \mathbf{1.33} \text{ volts.}$$

If we take into account the 5 c.m. free space at the sides of each electrode, and allow an equal amount as effective beneath, the cross-section of the electrolyte may be taken as

$$(75 + 5) \times (50 + 10) = 4{,}800 \text{ c.m}^2\text{.,}$$

and the resistance between two plates:

$$20 \times 6.04 \div 4{,}800 = 0.0252 \text{ ohms,}$$

and the drop $0.0252 \times 41.25 = \mathbf{1.04}$ volts.

This value is the more probable one of the two.

At the close of a deposition, neglecting the decreased thickness of the thin anode plates, the working distance is decreased by $1.5 \times 2 = 3$ centimeters, and the voltage drop between plates will then be:

$$\frac{20 \times 3.04}{4{,}800} \times 41.25 = \mathbf{0.52} \text{ volt.}$$

In both cases the voltage drop in contacts and conductors being 0.3 volt, the working voltage per tank will be:

	Volts.
At starting	**1.34**
At end	**0.82**
Average	**1.08**

The voltage needed at the generators can only be calculated when we assume a plan of grouping the 762 tanks. If we assume 110 volts to be desired at the generators, we could run 102 tanks in one series, which would give 7½ series. If we used 220 volts at the generators 2 series of 190 cells and 2 of 191 would absorb at starting 255 and 256 volts respectively, but when in regular running, with tanks in all stages of deposition, 205 and 206 volts. This would be a reasonable and practicable arrangement. In reality, at least one if not two additional tanks would be slipped into each series, for at least that number would be out of circuit continuously, being cleaned and made ready for re-starting.

(5) The amperes per tank would be:

$$0.75 \times 0.5 \times 2 \times 16 \times 110 = 1{,}320.$$

And the area of the main conductors in each series:

$$1{,}320 \div 2 = \mathbf{660} \text{ sq. m.m.} \quad (5)$$

(6) The part of the anode sheet immersed weighs 8,888 grams, of which 0.9 is 8,000 grams, and if the anode is an intermediate one it is corroded on both sides, and receives, therefore, 85 amps. of current. This current dissolves, per second:

$$0.00001036 \times 28 \times 85 = 0.024657 \text{ grams.}$$

And therefore the anode sheet will last

$$8{,}000 \times 0.024657 = 324{,}000 \text{ seconds.}$$

$$= \mathbf{90} \text{ hours.} \quad (6)$$

(7) The weight of deposit on both sides of a cathode plate is

$$75 \times 50 \times 2 \times 1.5 \times 7.6 = 85{,}500 \text{ grams.}$$

And the time required to deposit this, since it is deposited by 85 amps., is

$$85{,}500 \div 0.024657 = 3{,}467{,}600 \text{ seconds.}$$

$$= \mathbf{40} \text{ days } \mathbf{3} \text{ hours.} \quad (8)$$

(8) Each series requires 1,320 amps. at 205 volts, or

$$1{,}320 \times 205 \div 1{,}000 = 270.6 \text{ kilowatts.}$$

The three series therefore require 812 kilowatts, which will cost

$$\$25.00 \times 812 \div 365.25 = \$55.68 \text{ per day.}$$

An average cost of power per ton of iron refined of

$$\$55.68 \div 25 = \mathbf{\$2.23.} \quad (8)$$

The other items of cost in a well conducted refinery will about equal this sum, making the total cost of refining about $4.50 per ton of pure iron. With cheap soft steel used as the raw material, there is a striking possibility of such a process

being commercially practicable for furnishing one of the raw materials for producing the finest qualities of steel, the other raw material being washed pig metal of standard quality. We commend this possibility to the attention of the makers of fine steel.
